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Assessment of Design Modifications to Final Clothe the Soldier Rucksack

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Abstract

A modification from Velco® and strapping to a sewn attachment method for the shoulder straps of the Clothe the Soldier (CTS) Rucksack was evaluated for: load control, dynamic peak loading and pressure distribution to the torso. Quantitative assessment of these functional parameters was undertaken to compare the behaviour of a proposed modification to that of the currently fielded design to ensure no degradation in performance. This modification was proposed to address problems that have arisen with the current shoulder strap attachment when loads carried in the rucksack increased from 25 to approximately 45 kg.

The CTS load carriage system includes the Tactical Vest (TV), the Rucksack, and a Small Pack System which have been designed to be compatible. In addition to wearing the TV and one of the packs, soldiers are increasingly attempting to wear the Fragmentation Protection Vest (FPV), with Bullet Resistant Plates (BRP) beneath the TV and Rucksack.

The purpose of testing was to quantify any impact of the modified shoulder attachment design on the following parameters: a soldier's load control ability, the pressure distribution under the rucksack, the range of motion of the trunk or the mechanical energy cost of walking. Both CTS designs were tested dynamically on the Load Carriage Simulator and on the Compliance tester.

Results showed no significant effects on the load carriage parameters examined and consequently no significant change is anticipated in the CTS rucksack performance in terms of load control, pressure distribution, torso range of motion or energy cost should this modified shoulder strap attachment method be adopted.

Résumé

La modification proposée au mode de fixation des courroies d’épaules du sac à dos Habillez le soldat (HLS), visant à passer d’un mode de fixation par Velco® et sangle à un mode de fixation cousu, a été évaluée en fonction du contrôle de la charge, des pointes de charge dynamiques et de la répartition de la pression sur le torse. Une évaluation quantitative de ces paramètres fonctionnels a été effectuée pour comparer le comportement du mode de fixation proposé à celui en service, afin de déterminer s’il y avait diminution du rendement. La modification a été proposée pour régler les problèmes de fixation des courroies d’épaules qui sont survenus lorsque les charges transportées dans le sac à dos sont passées de 25 à environ 45 kg.

Le système de transport de charge HLS comprend la veste tactique (VT), le sac à dos et l’ensemble musette et sacs. Tous ces composants ont été conçus de manière à être compatibles. De plus en plus souvent, les soldats tentent de porter la veste pare-éclats (VPE) avec plaques pare-balles (PPB) en plus de la VT et du sac à dos.

Les essais visaient à mesurer l’impact du mode de fixation modifié des courroies d’épaules sur les paramètres suivants : capacité de contrôle de la charge par le soldat, répartition de la pression sous le sac à dos, amplitude du mouvement au niveau du torse et dépense d’énergie mécanique pendant la marche. Les deux modes de fixation ont été soumis à des essais dynamiques sur le simulateur de transport tactique et l’appareil d’essai de conformité de transport tactique.

Les résultats n’ont démontré aucun effet important sur les paramètres de transport de charge examinés. Par conséquent, si la modification au mode de fixation des courroies d’épaules est adoptée, on ne prévoit aucun changement important au niveau du rendement du sac à dos HLS en ce qui a trait au contrôle de la charge, à la répartition de la pression, à l’amplitude du mouvement au niveau du torse ou à la dépense d’énergie.

Executive Summary

A modification from Velco® and strapping to a sewn attachment method for the shoulder straps of the Clothe the Soldier Rucksack was evaluated for: load control, dynamic peak loading and pressure distribution to the torso. Quantitative assessment of these functional parameters was undertaken to compare the behaviour of a proposed modification to that of the currently fielded design to ensure no degradation in performance. This modification was proposed to address problems that have arisen with the current shoulder strap attachment when loads carried in the rucksack increased from 25 to approximately 45 kg.

The designs were assessed dynamically on two standardized tests, the Load Carriage Simulator and the Load Carriage Compliance tester. The purpose of the compliance testing was to quantify any effect of the modified shoulder attachment design on the walking compliance of the rucksack in order to determine if soldiers' range of motion in the trunk or mechanical energy cost of walking would be negatively (or positively) impacted. The tests provided a comparison of the resistance to motion for forward bending, lateral flexion and torsion around the vertical axis of the trunk with the two different shoulder attachment designs.

Results showed no significant effects on the load carriage parameters examined. Motion of the payload in the CTS as fielded and the CTS Mod configurations was contained within a volume of less than 6 mm^3. This extremely small displacement volume indicates that the in both cases, the payload very closely tracked the motion of the torso. The CTS Mod payload displacement in any direction was not significantly different than that of the CTS as fielded rucksack with the variation in results less than the manufacturers published system accuracy of 0.76 mm. Reaction forces and moments required to balance the dynamic loads on the soldiers was not significantly different between the CTS as fielded and the CTS Mod configurations. All peak pressures identified in the CTS pack were indistinguishable from those identified in the CTS Mod with the exception of in location 1. In this location, the CTS Mod pack trapped one of the metal buckles used to adjust the tightness of the tactical vests under the padding on the back panel. This did not reoccur in the testing of the CTS as fielded.

Overall, there were no significant differences on any of the load carriage parameters examined for the CTS as fielded and the CTS Mod configurations for the shoulder attachment design change. Consequently no significant change is anticipated in the CTS rucksack performance in terms of load control, pressure distribution, torso range of motion or energy cost should this modified shoulder strap attachment method be adopted.

Sommaire

La modification proposée au mode de fixation des courroies d’épaules du sac à dos Habillez le soldat (HLS), visant à passer d’un mode de fixation par Velco® et sangle à un mode de fixation cousu, a été évaluée en fonction du contrôle de la charge, des pointes de charge dynamiques et de la répartition de la pression sur le torse. Une évaluation quantitative de ces paramètres fonctionnels a été effectuée pour comparer le comportement du mode de fixation proposé à celui en service, afin de déterminer s’il y avait diminution du rendement. La modification a été proposée pour régler les problèmes de fixation des courroies d’épaules qui sont survenus lorsque les charges transportées dans le sac à dos sont passées de 25 à environ 45 kg.

Les deux modes de fixation ont été soumis à des essais dynamiques à l’aide de deux appareils d’essai normalisés soit le simulateur de transport tactique et l’appareil d’essai de conformité de transport tactique. L’essai de conformité visait à mesurer les effets du mode de fixation modifié sur la conformité à la marche du sac à dos, afin de déterminer s’il avait un impact négatif (ou positif) sur l’amplitude du mouvement au niveau du torse ou sur la dépense d’énergie mécanique du soldat pendant la marche. Les essais ont permis de comparer la résistance aux mouvements de flexion vers l’avant, de flexion latérale et de torsion autour de l’axe vertical du tronc des deux modes de fixation des courroies d’épaules.

Les résultats n’ont démontré aucun effet important sur les paramètres de transport de charge examinés. Le mouvement de la charge avec la configuration en service et la configuration modifiée était limité à un volume de moins de 6 mm^3. Ce très petit volume de déplacement indique qu’avec les deux configurations la charge suivait de très près les mouvements du torse. Le déplacement de la charge avec le sac à dos modifié, quel que soit le sens, n’était pas très différent du déplacement avec le sac à dos en service, et les différences dans les résultats étaient inférieures à la précision du système donnée par le fabricant, qui est de 0,76 mm. Les forces et les moments de réaction nécessaires pour équilibrer les charges dynamiques sur le dos du soldat n’étaient pas très différentes d’une configuration à l’autre. Les points de pression identifiés avec le sac à dos en service étaient

les mêmes que ceux identifiés avec le sac à dos modifié, à l’exception du point 1. À ce endroit, le sac à dos modifié a coincé une des attaches métallique qui servent à ajuster la veste tactique sous le matelassage du panneau arrière. Ce problème ne s’est pas reproduit lors de l’essai du sac à dos en service.

Dans l’ensemble, il n’y avait pas de différences marquées dans aucun des paramètres de transport de charge examinés entre le mode de fixation des courroies d’épaules du sac à dos en service et le mode de fixation modifié. Par conséquent, si la modification au mode de fixation des courroies d’épaules est adoptée, on ne prévoit aucun changement important au niveau du rendement du sac à dos HLS en ce qui a trait au contrôle de la charge, à la répartition de la pression, à l’amplitude du mouvement au niveau du torse ou à la dépense d’énergie.

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1 Assessment of CTS Shoulder Strap Attachment Modification

1.1 Purpose

A modification of the attachment method for the shoulder straps of the Clothe the Soldier Rucksack was evaluated for: load control, dynamic peak loading and pressure distribution to the torso. Quantitative assessment of these functional parameters was undertaken to directly compare the behaviour of a proposed modification to that of the currently fielded design to ensure no degradation in performance. This modification was proposed to address problems that have arisen with the current shoulder strap attachment because loads carried in the rucksack have increased from 25 to 30 kg up to approximately 45 kg.

The CTS load carriage system includes the Tactical Vest (TV), the Rucksack, and a Small Pack System which have been designed to be compatible. This permits various components to be combined to support the operational objectives at hand. In addition to wearing the TV and one of the packs, soldiers are increasingly attempting to wear the Fragmentation Protection Vest (FPV), with bullet resistant plates (BRP) beneath the TV and Rucksack.

The purpose of the compliance testing was to quantify any effect of the modified shoulder attachment design on the walking compliance of the rucksack in order to determine if soldiers' range of motion in the trunk or mechanical energy cost of walking would be negatively (or positively) impacted. The tests provided a comparison of the resistance to motion for forward bending, lateral flexion and torsion around the vertical axis of the trunk with the two different shoulder attachment designs.

Both CTS designs; as fielded and the proposed modification; were tested dynamically on the Load Carriage Simulator (LCSim) and the Compliance tester. The load carriage simulator is a pneumatically driven programmable shaker table which is able to move an anthropometrically sized and weighted torso. It is instrumented with a 6 degree of freedom load cell to record reaction forces and moments, Polhemus Fastrak® Motion tracking

system to record relative motion of kit items, and a Tekscan FScan® contact pressure measuring system. The LCSim was configured with a 50th percentile male manikin torso and programmed to replicate a walking speed of 5.6 kph (3.48 mph) for all dynamic tests. This corresponds to a typical step cadence of 1.8 Hz for a 50th percentile male. The Compliance tester is an automated device that bends a 50 percentile male manikin torso through repeatable motion patterns mimicking forward, lateral and torsional bending. It measures the resistance to the normal motions the torso makes during walking and ducking to calculate any effect on the mechanical energy cost of walking. A more complete description of the LCSim and instrumentation systems is given in Section 7, Appendix A.

2 Evaluation Methods

The CTS rucksack as fielded and the proposed CTS Mod were tested dynamically using the Load Carriage Simulator and the Load Carriage Compliance Tester. This section contains a description of these two test systems and the test methodology.

2.1 Load Carriage Simulator Testing

Representative loads were created for the TV and the rucksack. Total weight and weight distribution was maintained for both configurations tested.

2.1.1 Tactical Vest Load

Total mass of loaded TV was 15.2 kg (33.5 lb), consisting of:
(4) C7 mags,
(2) Fragmentation grenades,
(2) M18 smoke grenades,
(1) C9 drum,
(1) Bayonet
(1) Water bottle (full) with canteen cup
Plus additional steel and lead blocks in both front lower pouches, 2.5 kg per side.

2.1.2 Rucksack Payload

The payload was constructed in two identical sections, each consisting of 5 steel plates secured within a glued rigid Styrofoam™ box. The sections were strapped securely together with two 25 mm nylon webbing straps. Total mass of the payload was 45.7 kg (100.8 lb). The steel plates were placed such that the resultant center of mass was at the center of the rucksack volume.

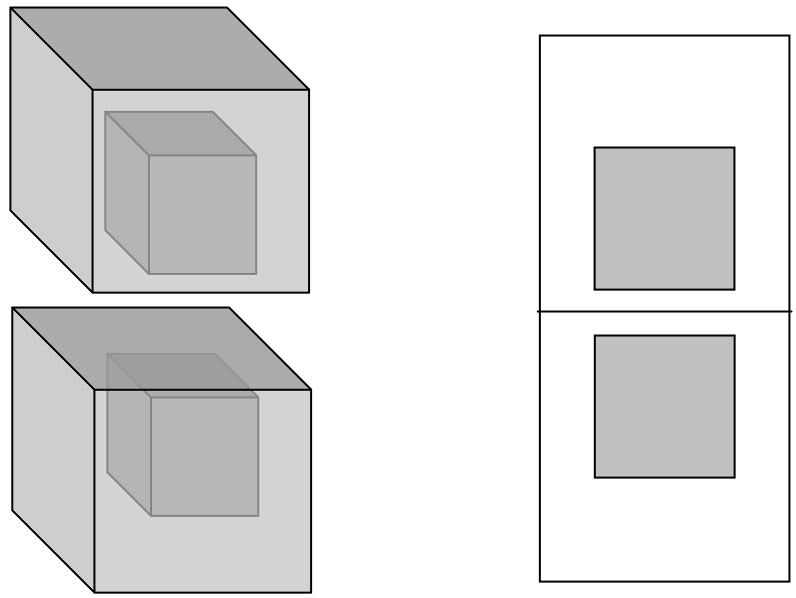


Figure 1. Schematic of the rucksack payload.

Testing was conducted using the Load Carriage Simulator. A brief description of the device and its instrumentation is included in the following section of the report and additional details may be found in Section 7 - Appendix A.

2.1.2 Torso Specifications

A 50th percentile male manikin form, as defined by Safework™ anthropometric software was selected for LC simulator testing. The manikin was comprised of a head and trunk section, with arms truncated in the mid-humeral region and legs extending to just below the buttocks.

The human model consisted of a fibreglass outer shell with expandable poured polyurethane foam filling. Appropriate mass distribution was achieved by thoroughly mixing stone aggregate with the interior foam. A vertical cylindrical cavity was created in the manikin to allow for mounting of a 6 degree-of-freedom load cell. The neutral axis of the load cell was positioned at the approximate location of the manikin's hips. This load cell was further mounted on a single axis articulating vice, which permitted the manikin

and LC system to be placed in a balanced anterior body lean position for load carriage. Finally, the surface of the manikin was covered with a 5 mm thickness of Bocklite™, a synthetic skin-like material used in prosthetics, to approximate the compressive response of human skin over bone.

2.1.3 Dynamic Test Protocol

The LC Simulator consists of the previously described rigid manikin, mounted on a programmable displacement platform. This platform rests on three air cylinders that allow vertical motion as well as rotation about the x (anterior/posterior) and y (medial/lateral) axes. A computer-controlled vertical displacement pattern (+/- 25 mm amplitude, 1.8 Hz frequency) simulates marching, and linear displacement transducers provide positional information for the control system. Feedback control is accomplished by varying the differential pressure across each cylinder face. The duration of one LC System test was typically 1200 seconds, with data recorded at 10 seconds (initial data set), and at each 300 second interval. Sampling rate for all data collection was 55 Hz and the duration was 10 seconds (minimum).

2.1.4 Relative Displacement of LC System and Torso

An electromagnetic position tracking system (Fastrak™ by Polhemus Incorporated) was used to provide three dimensional displacement data of the rucksack payload. The source for the Fastrak™ was affixed with nylon screws to the underside of the left arm of the manikin. All compression straps on the rucksack were tightened securely and the final positions marked on the webbing. A Fastrak™ sensor was secured to the top of the Styrofoam payload. Displacement data, for the payload with respect to the manikins' torso, was recorded for 10 seconds at 55 Hz for a minimum of three trials during the testing. Direct comparison of Fastrak™ positional data with data collected from an opto-electric positional recording system (Optotrak™ by Northern Digital Incorporated) with high precision (RMS error <0.01 mm) provided an RMS error for Fastrak™ data of 0.65 mm.

2.1.5 Reaction Forces and Moments

Ground reaction forces and moments were collected using a 6 degree-of-freedom load cell (AMTI Incorporated) based on a body fixed coordinate system located at the hip and oriented along the long axis of the trunk. The outcomes from this instrumentation were reported in terms of hip reaction forces in the Fx (forward and back), Fy (side to side), and Fz (up and down) directions. Similarly, the reaction moments are also measured and reported as Mx (lateral moments), My (flexion/extension moments), and Mz (torsional) moments.

Two factors affect the moments and forces transmitted through the load cell: the motion and mass of the moving bodies. In the LCSim, the mass of the torso creates significant reaction forces and moments under the imposed displacement from the positioning actuators. This is in addition to the forces needed to accelerate the payload itself. This body inertia is a constant effect for the two rucksack designs systems tested and so results may be compared directly.

2.1.6 Skin Contact Pressures

An F-Scan™ pressure sensor system (Tekscan Incorporated) was used to acquire contact pressure data on the manikin skin over the anterior shoulder, posterior shoulder, scapula, hips, upper and lower back regions. The F-Scan™ system uses a matrix of force sensitive resistors, arranged in a rectangular pattern and contained between two flexible sheets. At full size, there are 96 force sensitive resistors spaced over a region 206 mm by 76 mm. When the thin polymer in each element is compressed, there is a change in the element. This change is sensed by system software and is recorded as a load normal to the sensor surface, based on individual calibration for each sensor. Information is transferred to the computer through a signal processing unit and cable to a computer card. This information can be replayed in "movie" format, which can give a dynamic measurement of force, average and peak pressures, active area, or duration of contact. Previous testing at Queen’s University (Stevenson et al., 1996, Hadcock, 2002) has found the F-Scan™ system

standard error of the mean to be 9.6% for average pressures and 14% for peak pressures. Also, use of the sensors on a curved surface lead to a 9% standard error of the mean for average pressure results (MacNeil, 1996).

For this testing, pressure data were reported in terms of a peak dynamic pressures (kPa) and the average pressure over all active cells of the sensors (kPa) in the anatomical areas of interest. Research has shown that blood occlusion can occur when tissues are loaded at an average pressure of 14 kPa for 8 hours[1]. Average skin contact pressures of 20 kPa have also been associated with discomfort in 95 % of a test sample.

2.1.7 Strap Forces

During the testing, waist belt strap force tension transducers were placed in-line in the left half of the waist belt, free of any hip/kidney padding and in the both the right and left shoulder strap webbing. Output from the strap force transducers was amplified by a Keithley MetraByte DATAQ system (Keithley MetraByte Instruments Incorporated) and recorded digitally as part of the test record. The load in the rucksack was higher than typically used in previous testing and so a volunteer donned the instrumented rucksack and adjusted the straps to their satisfaction. These strap tension settings were used in all subsequent trials for this test series. The waist belt was set to a tension of 75 +/- 5 N and the shoulder strap tension was set to122+/-5N for all trials. These load cells are inserted directly inline with the strap and are designed to ensure all load passes through the device.

During testing, the hip stabilizer straps, sternum strap, and load lifter straps were preset to 90 N, 22 N, and 60 N respectively using a Chatillon® pull gauge. These straps are identified as # 3, # 4 and # 5 in Figure 2.

[1] Holloway, JA., Daly, CH., Kennedy, D., and J. Chimoskey. (1976). Effects of external pressure loading on human skin blood flow. . *Journal of Applied Physiology* **40**: 596-600.

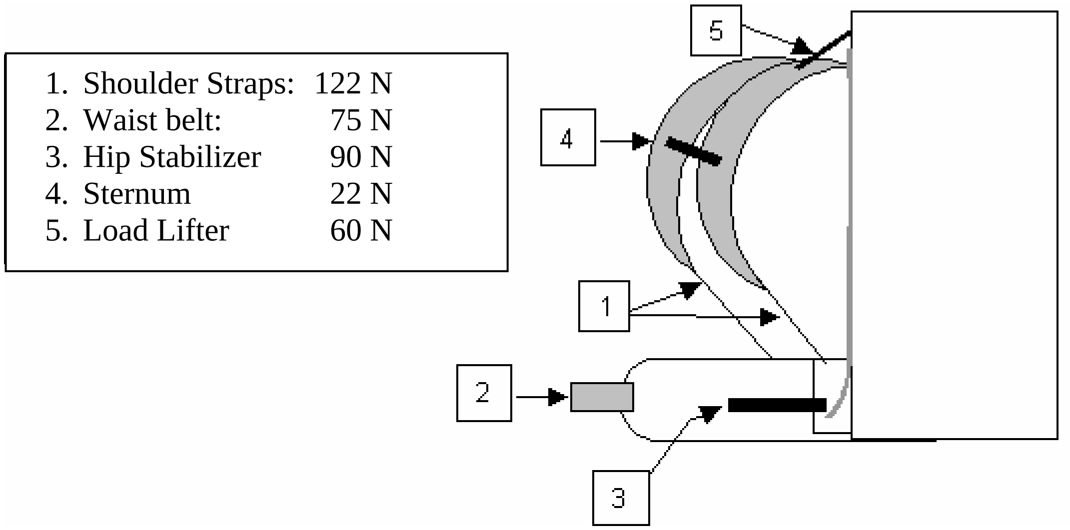


Figure 2. Location and preset tensions of ILBE pack straps

2.1.8 LC Simulator Testing Conditions

There were two testing conditions: the CTS as fielded (Velcro) where the shoulder strap attachment is held in place by Velcro, and the CTS Modified (sewn) were the shoulder strap attachment is sewn into place. Both testing conditions were subjected to identical simulated walking patterns of forced displacement.

Table 1. Description of Rucksack Test Parameters

Config. ID	**Rucksack**	**Payload**	**Tactical Vest**	**Fast Walking – 1.8 hz**
A	CTS as Fielded – Velcro shoulder strap attachment	45 kg	15 kg	+/-25.0 mm Amplitude, 1.8 Hz
B	Modified CTS Sewn shoulder straps	45 kg	15 kg	+/-25.0 mm Amplitude, 1.8 Hz

2.2 Compliance Testing

The purpose of the compliance testing was to quantify any effect of the modified shoulder attachment design on the walking compliance of the rucksack in order to determine if soldiers' range of motion in the trunk or mechanical energy cost of walking would be negatively (or positively) impacted. The tests provided a comparison of the resistance to motion for forward bending, lateral flexion and torsion around the vertical axis of the trunk with the two different shoulder attachment designs.

Both rucksacks were tested unloaded to avoid measuring any resistance to motion due to the stiffness of the load. The position of hip belt and shoulder straps was marked on the test apparatus and all testing was performed with the belt and shoulder straps in these positions. The waist belt, right and left shoulder straps were tightened to the tensions shown in Table 1 and measured with inline strap transducers. All other straps were tightened to preset levels with a Chatillon® pull gauge.

Table 2. Stiffness Tester Strap Tensions

1.	Shoulder Strap	22 N
2.	Waistbelt	32 N
3.	Hip Stabilizer	32 N *
4.	Sternum Strap	18 N *
5.	Load Lifter	20 N *

* Tension value estimate, these are estimated residual tensions when pulled with 15lbf, 4lbf and 5 lbf values on a Chatillon pull gauge respectively.

3 Results

3.1 Compliance Testing Results

During walking, the human body has a recognizable cyclic motion that permits the body to conserve energy by converting potential energy into kinetic and back into potential energy at different points in the gait cycle. The counter rotation of the shoulders when the hip swings forward, conserves angular momentum of the overall system, minimizing the energy required. These twisting motions occur on all three axes of the body. Simply immobilizing the upper body with an extremely stiff frame, as if it were lashed to a back board, has been shown to increase the energy demand during walking as well as increase personal discomfort (Inman et al.). Just as the stiffness or compliance of a spring reflects the level of force required to stretch it to a certain length, the compliance of a load carriage system reflects the force the body must exert to deflect the rucksack and TV through the range of motions required for normal walking. Figures 3, 4 and 5 directly compare the stiffness of the CTS rucksack with the two different attachment strategies for the three orthogonal axes of motion. Results are given in terms of the average moment needed to induce a degree of bend in each direction. The total amount of bend is based on the typical bend experienced during walking.

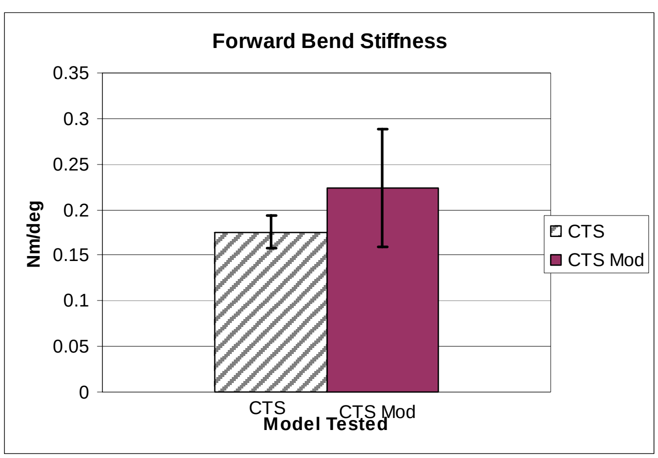


Figure 3. Forward Bending Stiffness

Error bars are defined by 2 standard deviations of the calculated slope from three independent trials. Only when results fall outside the overlap of the error bars are the differences significant.

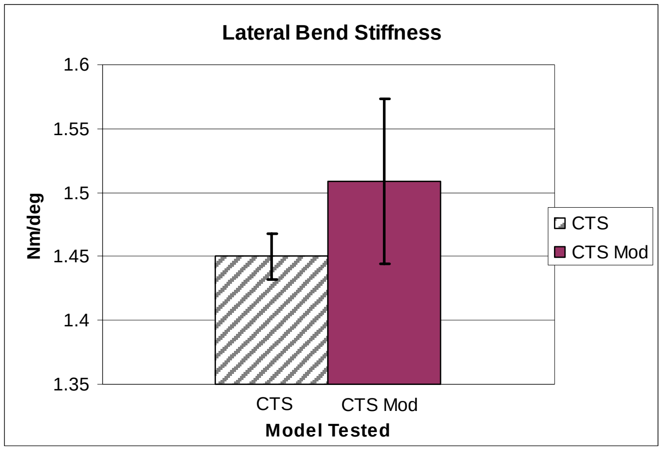


Figure 4. Lateral Bending Stiffness

Error bars are defined by 2 standard deviations of the calculated slope from three independent trials. Only when results fall outside the overlap of the error bars are differences significant.

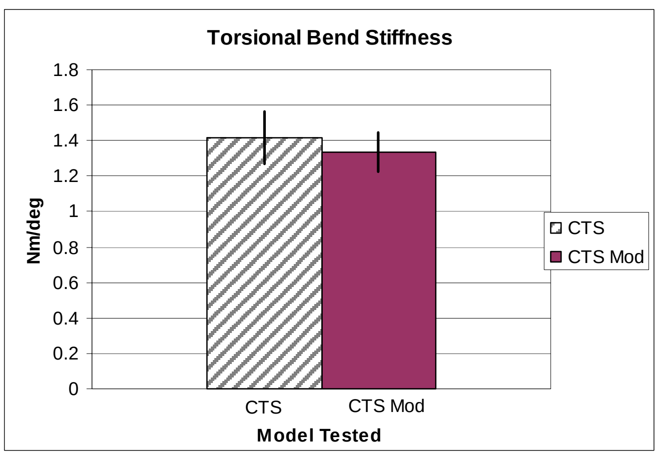


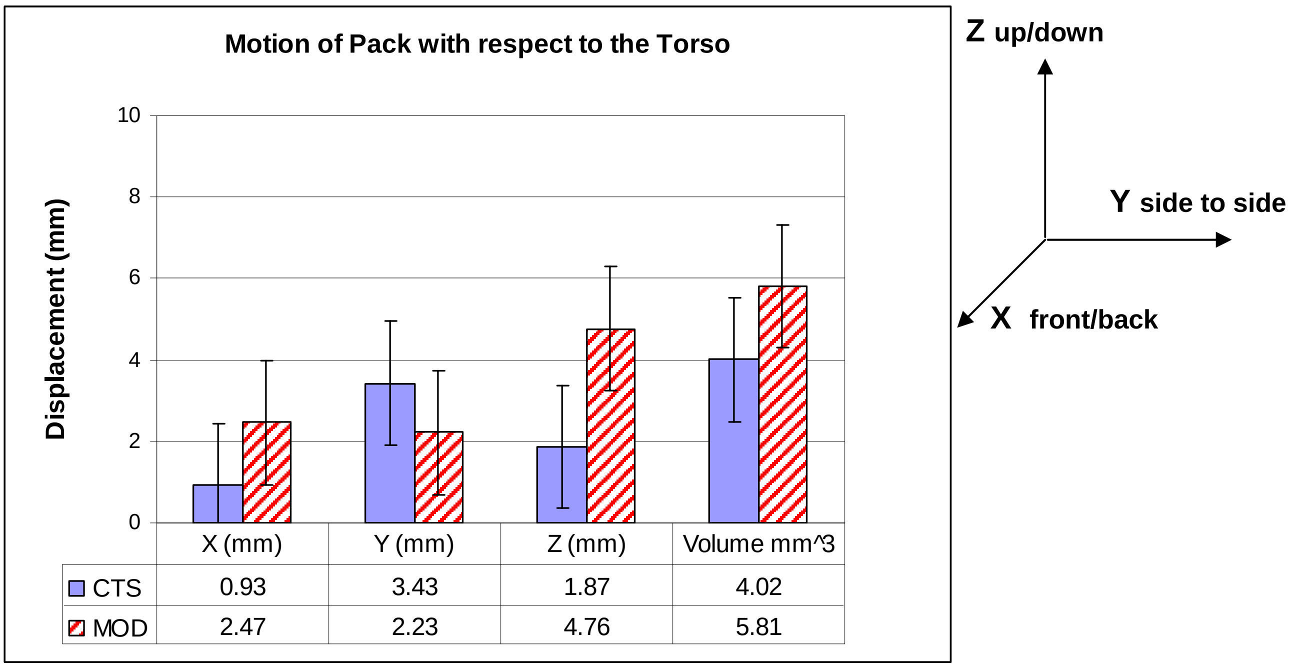
Figure 5. Torsional Bending Stiffness

Error bars are defined by 2 standard deviations of the calculated slope from three independent trials. Only when results fall outside the overlap of the error bars are differences significant.

3.2 Dynamic Testing Results

3.2.1 Load Control – Relative Displacements of Load

The ability of a soldier to control the motion of the payload carried in the rucksack impacts directly on their agility and comfort. Position of the payload with respect to the torso was tracked in three dimensions and the maximum relative position was then calculated over a series of 10 cycles. When relative motion of the payload for the two configurations was compared, no significant difference was found. In both cases the payload closely tracked the motion of the torso moving in all cases moving less than 5 mm away from the body in any direction. Figure 6 contains a summary of the relative motion results.



	X (mm)	Y (mm)	Z (mm)	Volume mm^3
CTS	0.93	3.43	1.87	4.02
MOD	2.47	2.23	4.76	5.81

Figure 6 Comparison of Relative Displacements

Error Bars represent +/- 0.79 mm, which is the manufacturers reported accuracy of the Fastrak device. Differences are significant if the error bars do not overlap.

3.2.2 LC Sim Reaction Forces and Moments

The load cell at the base of the Load Carriage Simulator measures the magnitude of the forces that would have to be exerted by a soldier to counteract the dynamic forces generated by load carried in the load carriage system LCS. Each different LCS creates a

different distribution of mass and a different motion of that weight. This combines to create a particular muscular demand in the body to balance the dynamic load.

Figure 8 to figure 13 summarize the reaction forces measured at the approximate location of the hip. They are reported in terms of a body fixed coordinate system with Z being the vertical, X being forward/backward, and Y being side to side.

For each configuration, the torso of the LCSim was rotated about the Y axis to balance the load, reducing My to 0. This replicates what humans do when we assume a forward lean to balance loads carried on the torso.

Forces and moments are reported in terms of both the average value experienced by a user and the magnitude of the dynamic range. Figure 7 below shows a typical force trace. The range magnitude was calculated by determining the average of twenty cyclic maximums and minimums and then calculating the average maximum minus the average minimum.

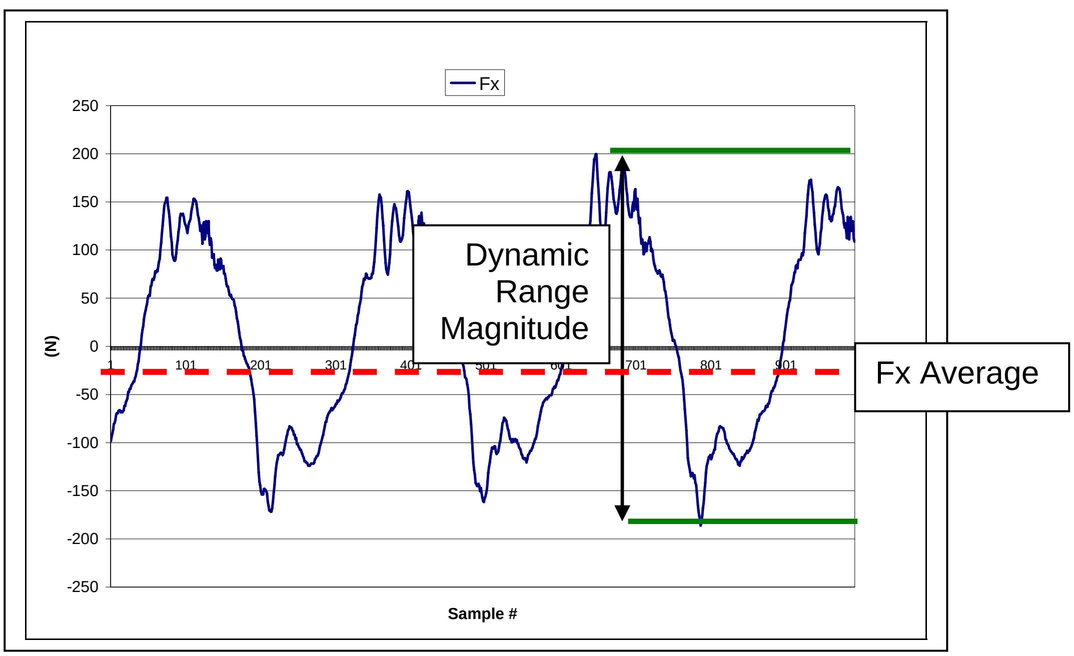
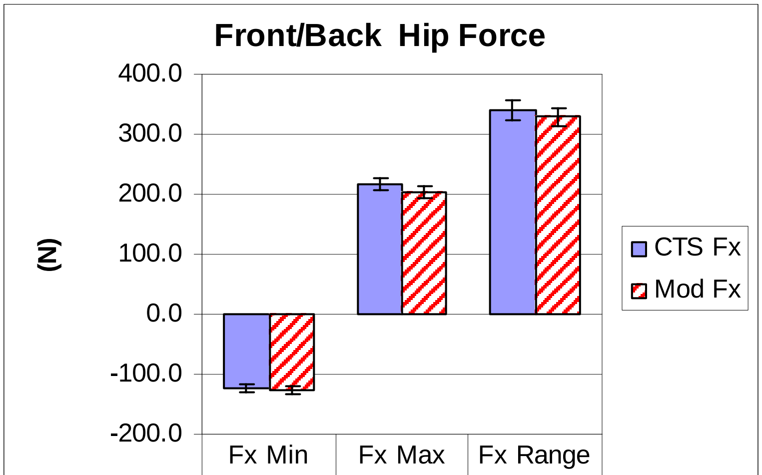
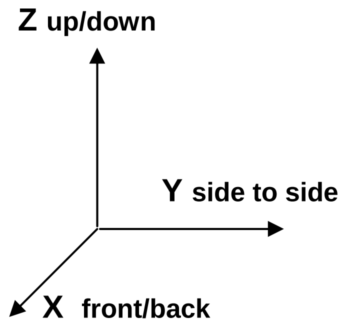


Figure 7. Definition of Dynamic Range

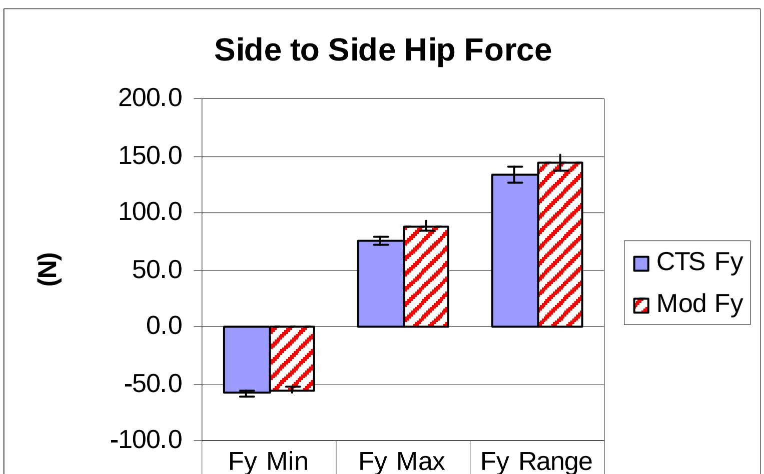




	Fx Min	Fx Max	Fx Range
CTS Fx	-124.2	216.6	340.8
Mod Fx	-125.7	202.8	328.5

Figure 8. Front/Back Hip Force Dynamic Range

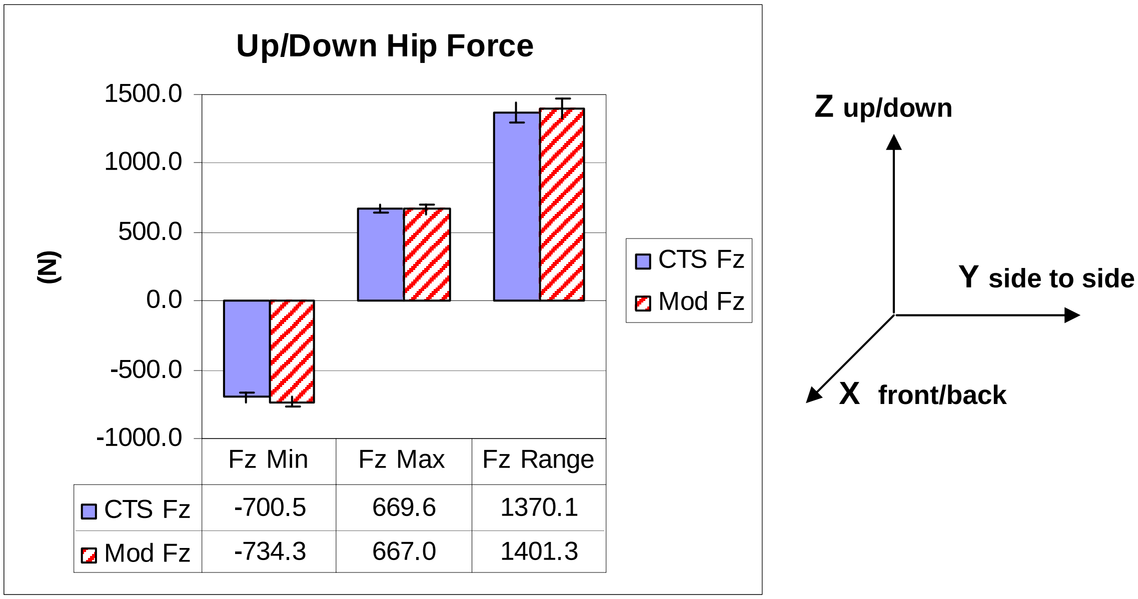
Fx is the forward backward force (anterior/posterior) with respect to the body. Error bars indicate +/-5%.



	Fy Min	Fy Max	Fy Range
CTS Fy	-58.4	74.9	133.3
Mod Fy	-55.7	87.9	143.6

Figure 9. Side to Side Hip Force Dynamic Range

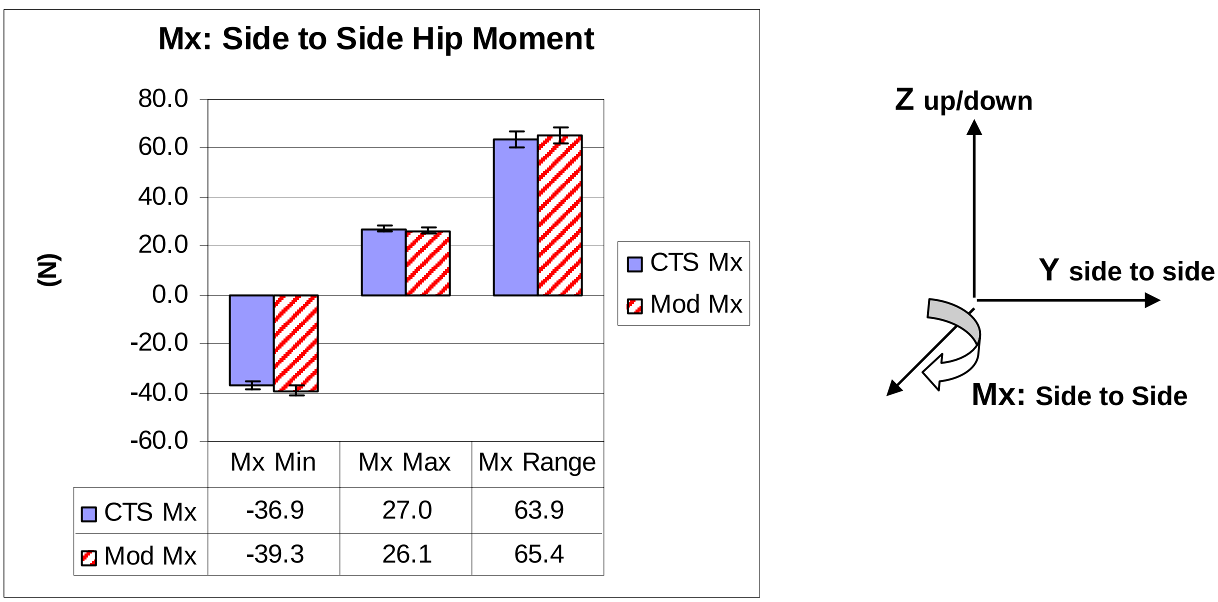
Fy is in the side to side force (medial/lateral) with respect to the body. Error bars indicate +/-5%.



	Fz Min	Fz Max	Fz Range
CTS Fz	-700.5	669.6	1370.1
Mod Fz	-734.3	667.0	1401.3

Figure 10. Vertical Hip Force Dynamic Range

Vertical force is with respect to the vertical axis of the body. Error bars indicate +/-5%.



	Mx Min	Mx Max	Mx Range
CTS Mx	-36.9	27.0	63.9
Mod Mx	-39.3	26.1	65.4

Figure 11. Magnitude of Mx Dynamic Moment

Mx is the restoring moment about the X axis, experienced as a side to side twist. Error bars indicate +/-5% error.

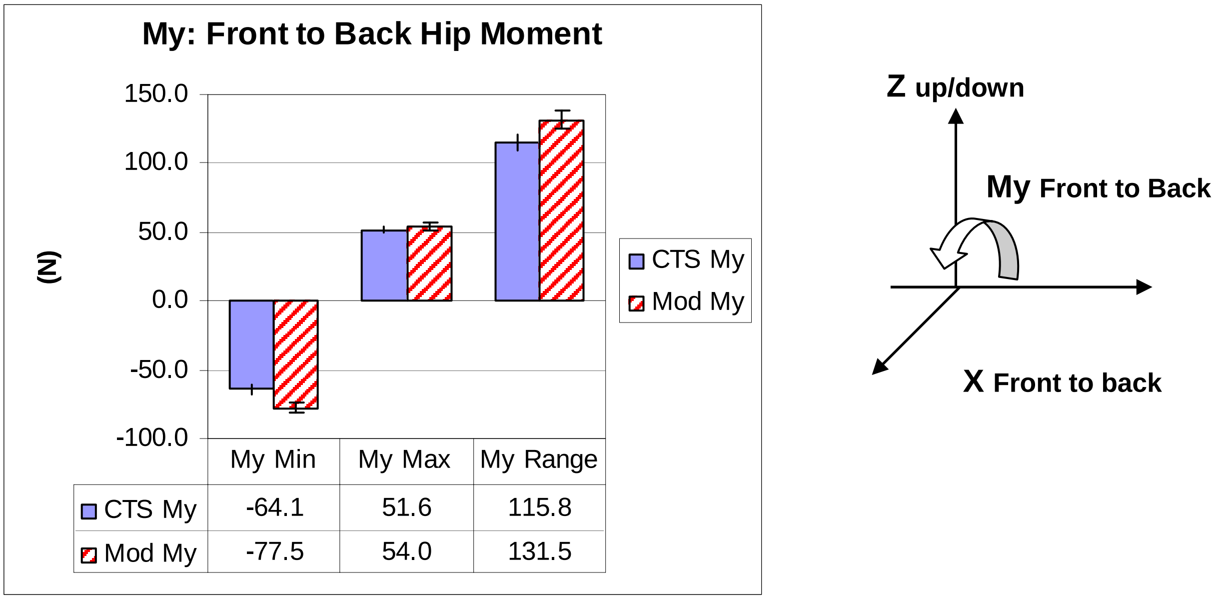


Figure 12. Magnitude of My Dynamic Moment

My is the restoring moment about the X axis, experienced as a side to side twist. Error bars indicate +/-5% error.

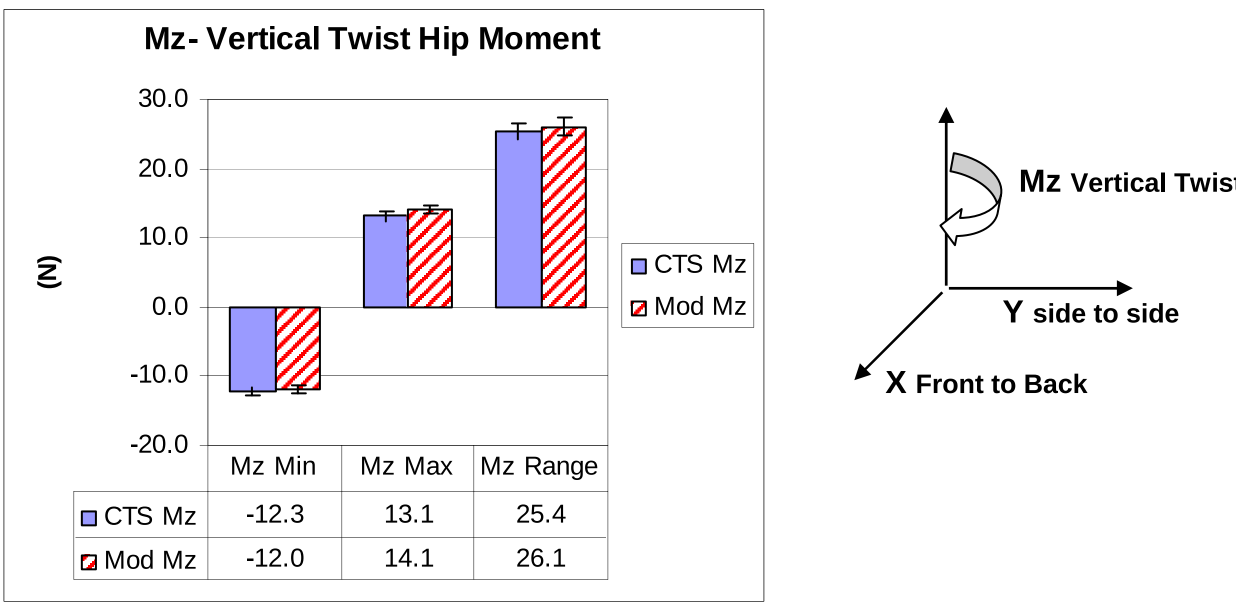


Figure 13. Magnitude of Mz Dynamic Moment

Mz is the restoring moment acting about the Z axis (about the vertical axis) of the body. Error bars indicate +/-5% error.

3.3 Pressure Results

A total of 15 locations on the torso were monitored for contact pressures. Figure 14 below defines the locations of the FScan sensors. The location and magnitude of the peak and average pressures are given in Figures 15 and 16 respectively.

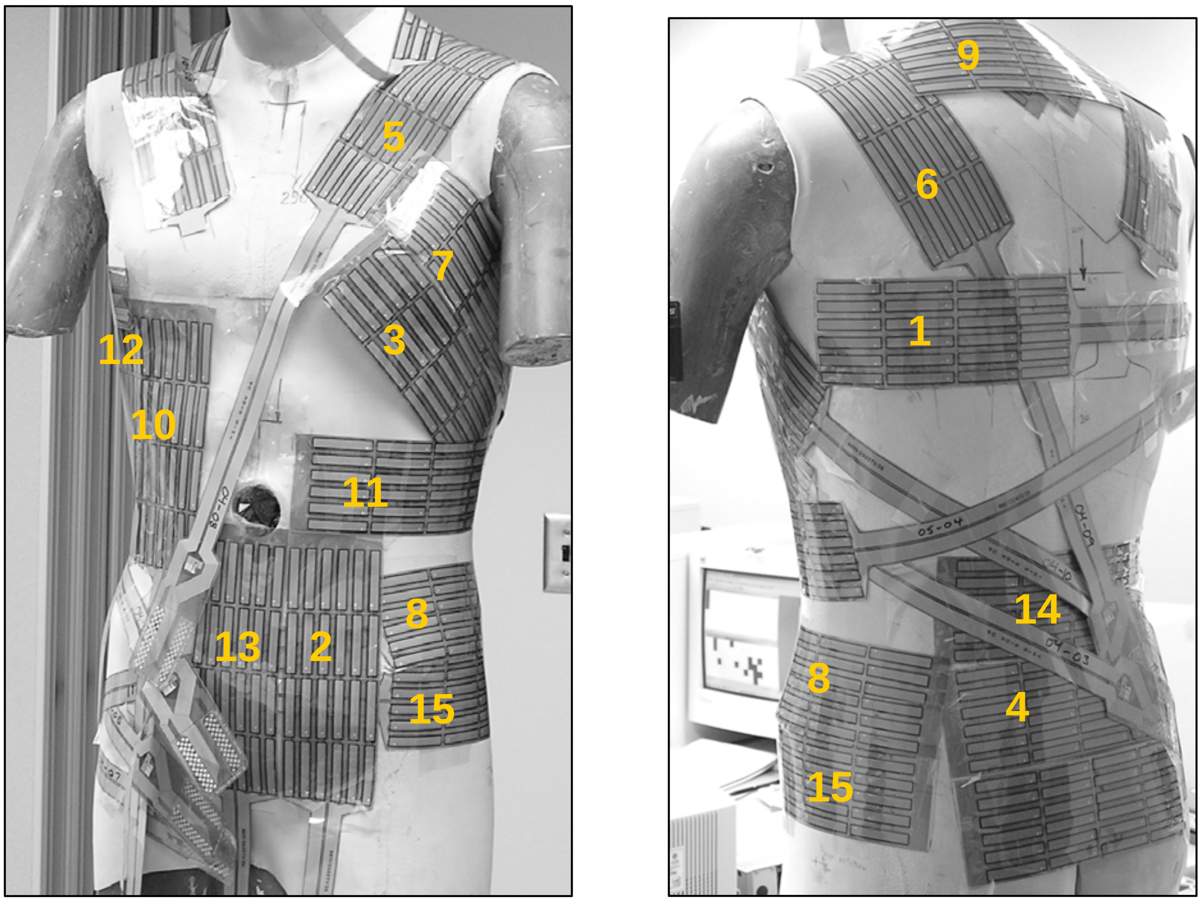


Figure 14. Pressure Sensor Locations

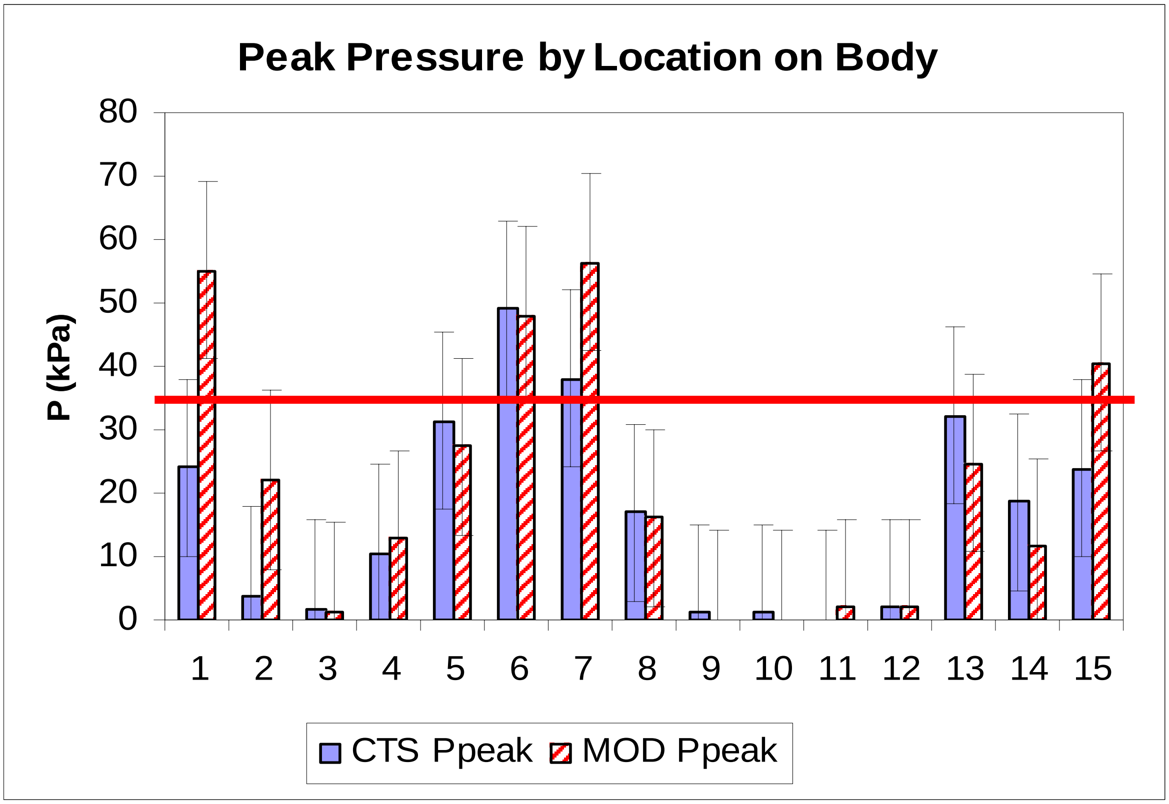


Figure 15. Peak pressure on the body at all monitored sites.

These values correspond to the 'hot spots' which are locations experiencing the highest local pressure on the regions of the body that were monitored. Maximum acceptable peak pressure is considered to be 34 kPa. Error bars show +/- 14 kPa which is the tested accuracy of the pressure sensors.

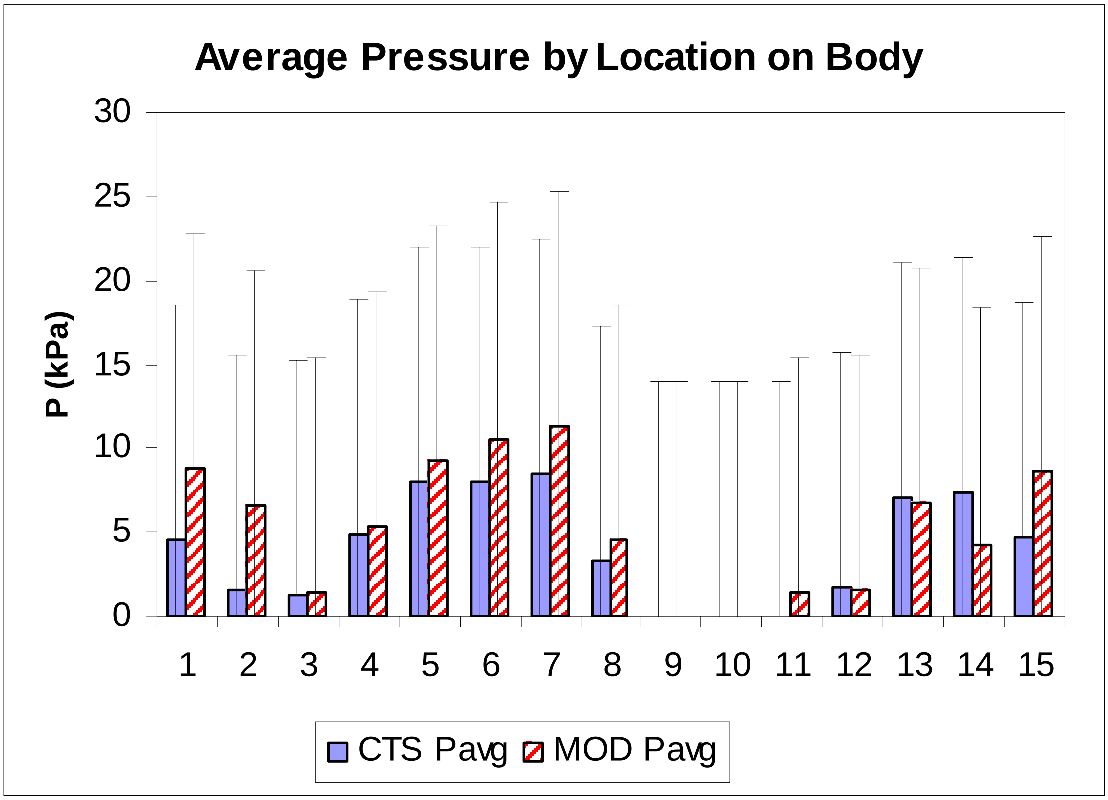


Figure 16. Average pressure on the body at all monitored sites.

These values correspond to the total force experienced on each sensor location, divided by the contact area. Average pressures should typically be less than 20 kPa for continuous exposure conditions. Error bars show +/- 14 kPa which is the tested accuracy of the pressure sensors. Average pressures on sensors 9 and for both the CTS and MOD were so low as to be effectively 0. This was also the case for sensor location 11 for the CTS.

4 Discussion

4.1 Displacement

Agility is the ability of a soldier to quickly change their direction of motion and have their load instantly track with them. Large relative displacements of the rucksack can influence a user in several ways. First, there is a direct effect on a user's agility. Mobile items dissipate energy and require additional muscular effort to control their motion. As well, relative motion between a wearer and the rucksack may indicate a potential for chaffing if the relative motion of payload is transmitted directly to the skin surface.

Motion of the payload in the CTS as fielded and the CTS Mod configurations was contained within a volume of less than 6 mm^3. This extremely small displacement volume indicates that the in both cases, the payload very closely tracked the motion of the torso. The CTS Mod payload displacement in any direction was not significantly different than that of the CTS as fielded rucksack with the variation in results less than the manufacturers published system accuracy of 0.76 mm.

4.2 Forces and Moments Discussion of Results

Reaction forces and moments are measured at a load cell at the approximate ‘hip’ of the Load Carriage Simulator and quantify the forces required to balance the dynamic loads on the soldier. In the human, these forces and moments at this joint are generated by the leg and hip muscles. These forces and moments are in response to accelerating and decelerating the mass of the payload.

Figures 8 through 13 summarize the direct comparison of the CTS as fielded pack to the CTS Modified. Virtually all of these plots show that the forces and moments and are not statistically significantly affected by this design change. The overlap of the error bars on the plots indicates that there is no significant difference in the performance of these two designs as the difference measured is less than the experimental error.

4.3 Pressure – Average and Peak Discussion of Results

From the results summarized in the peak and average pressure plots, Figures15 and 16, all peak pressures identified in the CTS pack were indistinguishable from those identified in the CTS Mod with the exception of in location 1. In this location, the CTS Mod pack trapped one of the metal buckles used to adjust the tightness of the tactical vests under the padding on the back panel. This did not reoccur in the testing of the CTS as fielded. This single region of high pressure (> 50 kPa) also affects the calculation of the average pressure in this location and its’ effect is seen in the average pressure plot, Figure 16.

The only other location which showed a variation in the average pressure greater than the measurement error in these sensors was at location 2 which occurs at the front of the body beneath the unpadded portion of the waist belt, underneath the area where the waist belt buckle was located. Once again, the peak pressure in this location, which occurs in an area less than 2.5 cm^2 tends to have a large effect on the calculation of the average pressure when there is minimal contact in a region. It is felt that the difference between the two rucksack designs indicated by results is more from an artefact in the way average pressure is calculated rather than a difference in the behaviour of the particular pack design.

5 Conclusions and Recommendations

Analysis of the displacement results leads to the following conclusions:

1. There was no significant difference in the relative motion of the payload, in the X (anterior/posterior), Y (side to side) or Z (vertical) direction in the CTS rucksack with the modification to a sew attachment.
2. The volume of motion of the payload was not significantly different in the CTS as fielded and the CTS with modified attachment. In both cases it was less than 6 mm^3 which reflects an excellent level of load tracking.

Analysis of the hip reaction force and moment results during normal cyclic gait leads to the following conclusion:

1. There was no significant change in the load control performance of the CTS rucksack with the modification to a sewn shoulder strap attachment.

Analysis of the Pressure results leads to the following conclusion:

1. Average Pressure and Peak pressures experienced by the body were not significantly affected.

Analysis of the Stiffness results leads to the following conclusions:

1. Forward bending stiffness was not significantly affected by the proposed modification.
2. Lateral bending stiffness was not significantly affected by the proposed modification
3. Torsional bending stiffness was not significantly affected by the proposed modification.

In summary, the proposed modification of the shoulder strap attachment did not have a significant impact, either negatively or positively, on the load carriage performance of the CTS rucksack. No detrimental effects are anticipated.

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7 Appendix A

7.1 Load Carriage Simulator Description

7.1.1 Torso Specifications and Preparation

A family of four anthropometric manikins (5th and 50th percentile females, and 50th and 95th percentile males, as defined by Safework™ anthropometric software) were constructed for LC simulator testing. Each manikin was comprised of a head and trunk section, with arms truncated in the mid-humeral region and legs extending to just below the buttocks.

These human models consisted of a fibreglass outer shell with expandable poured polyurethane foam filling. Proper mass distribution was achieved by thoroughly mixing aggregate with the interior foam. A vertical cylindrical cavity was created in each manikin to allow for mounting of a six degree-of-freedom load cell. In each case, the neutral axis of the load cell was positioned at the approximate location of the manikin's hips. This load cell was further mounted on a single axis articulating vice, which permitted the manikin and LC system to be placed in a balanced anterior body lean position for load carriage. Finally, the surface of each manikin was covered with a 5 mm thickness of Bocklite™, a synthetic skin-like material used on prosthetics, to approximate the compressive response of human skin over bone.

7.1.2 Test Protocol

The LC Simulator (Figure 2.1-2) consists of the previously described rigid manikin, mounted on a programmable displacement platform. This platform rests on three air cylinders which allow vertical motion as well as rotation about the x (anterior/posterior) and y (medial/lateral) axes. A computer controlled vertical displacement pattern (+/- 25.4 mm amplitude, 1.8 Hz frequency) simulates marching, and linear displacement transducers provide positional information for the control system. Feedback control is accomplished by varying the differential pressure across each cylinder face.

Each LC manikin was loaded with the payload, positioned on the simulator and properly adjusted. A standard LC Sim test is comprised of multiple intervals of 120 seconds of simulated walking was performed. The sampling rate for all data collection is 55 Hz and the duration is 10 seconds (minimum). Outcome measures from the LC Sim test consist of; the relative displacement between manikin and the LC system; contact pressures on the shoulders, upper back, and lower back; and hip reaction forces and moments.

7.1.3 Torso Specifications

A family of four anthropometric manikins (5th and 50th percentile females, and 50th and 95th percentile males, as defined by Safework™ anthropometric software) was constructed for LC simulator testing. Each manikin was comprised of a head and trunk section, with arms truncated in the mid-humeral region and legs extending to just below the buttocks. The 50 percentile male torso was used for this test.

These human models consisted of a fiberglass outer shell with expandable poured polyurethane foam filling. Appropriate mass distribution was achieved by thoroughly mixing stone aggregate with the interior foam. A vertical cylindrical cavity was created in each manikin to allow for mounting of a six degree-of-freedom load cell. In each case, the neutral axis of the load cell was positioned at the approximate location of the manikin's hips. This load cell was further mounted on a single axis articulating vice, which permitted the manikin and LC system to be placed in a balanced anterior body lean position for load carriage. Finally, the surface of the manikin was covered with a 5 mm thickness of Bocklite™, a synthetic skin-like material used in prosthetics, to approximate the compressive response of human skin over bone.

7.1.4 Dynamic Test Protocol

The LC Simulator consists of the previously described rigid manikin, mounted on a programmable displacement platform. This platform rests on three air cylinders that allow vertical motion as well as rotation about the x (anterior/posterior) and y (medial/lateral) axes. A computer-controlled vertical displacement pattern (+/- 25 mm amplitude, 1.8 Hz frequency) simulates marching, and linear displacement transducers provide positional information for the control system. Feedback control is accomplished by varying the differential pressure across each cylinder face.

7.1.5 Relative Displacement of LC System and Torso

An electromagnetic position tracking system (Fastrak™ by Polhemus Incorporated) was used to provide three dimensional displacement data. The source for the Fastrak™ was affixed with nylon screws to the underside of the left arm of the manikin. All compression straps were tightened securely. A Fastrak™ sensor was then attached to the upper surface of a polystyrene insert. This insert was placed on top of the payload and held in place with 2 inch long steel pins driven through the four sides of the rucksack into the polystyrene block. The inner liner and the lid of the rucksack were tightened securely over the payload and insert. Displacement data, for the payload with respect to the source, was recorded for 10 seconds at 55 Hz over the duration of the test. The payload and insert were not disturbed between the with/without abdominal plate tests thus allowing a direct comparison of the relative displacement of the payload under the two conditions.

7.1.6 Reaction Forces and Moments

Ground reaction forces and moments were collected using a 6 degree-of-freedom load cell (AMTI Incorporated) based on a body fixed coordinate system located at the hip and oriented along the long axis of the trunk. The outcomes from this instrumentation were reported as reaction forces in the Fx (forward and back), Fy (side to side), and Fz (up and down) directions.

Reported reaction forces were normalized by dividing them by the payload carried in the load carriage system. The resultant *normalized* values were expressed as Nm/kg for moments and N/kg for forces. A normalized force of 9.81 N/kg indicated a force of 9.81 N for each kilogram of load carried.

7.1.7 Skin Contact Pressures

An F-Scan™ pressure sensor system (Tekscan Incorporated) was used to acquire contact pressure data on the manikin skin over the anterior shoulder, posterior shoulder, scapula and low back region. Figure 2.2-2 shows the orientation of the F-Scan™ 9810 pressure sensors, which were affixed to the manikin with a non-permanent adhesive. The F-Scan™ system uses a matrix of force sensitive resistors, which are arranged in a rectangular pattern and contained between two flexible polyester plastic sheets. At full size, there are 96 force sensitive resistors spaced over a region 206 mm by 76 mm. When the thin polymer in each element is compressed, there is a change in the element. This change is sensed by system software and is recorded as a load normal to the sensor surface, based on individual calibration for each sensor. Information is transferred to the computer through a signal processing unit and cable to a computer card. This information can be replayed in "movie" format, which can give a dynamic measurement of force, average and peak pressures, active area, or duration of contact. Previous testing at Queen’s (Stevenson et al., 1996, Hadcock, 2002) has found the F-Scan™ system standard error of the mean to be 9.6 % for average pressures and 14 % for peak pressures. Also, use of the sensors on a curved surface leads to a 9% standard error of the mean for average pressure results (MacNeil, 1996).

For this testing, pressure data were reported in terms of peak dynamic pressures (kPa) and average pressure over all active cells of the sensors (kPa) in the anatomical areas of interest.

7.1.8 Strap Forces

During the setup phase of the LC Simulator testing, strap force tension transducers were placed in-line in both shoulder straps and the left half of the waist belt, free of any hip/kidney padding. Attachment of the transducers was accomplished by placing a pin through an attachment ring in the end of the carrier material of each transducer, ensuring

that all tension in the strap was transmitted through the transducer. Output from the force transducers was amplified by a Keithley MetraByte DATAQ system (Keithley MetraByte Instruments Incorporated) and recorded digitally as part of the test record. Initial settings of 60 +/- 5 N in the shoulder straps and 90 +/- 5 N in the waist strap were used for all load carriage trials. The force transducers were constructed with four foil style strain gauges, attached in a full Wheatstone bridge configuration to a rounded I-shaped 6061-T6 aluminium carrier with a length of 38.00 mm and thickness of 1.14 mm. Static testing of the transducers showed they were highly linear (r^2 >0.9995) with a small standard error (<0.01 V).

7.1.9 Relative Displacement of LC System and Torso

An electromagnetic position tracking system (Fastrak™ by Polhemus Incorporated) was used to provide three dimensional displacement data. The source for the Fastrak™ was affixed with nylon screws to the underside of the left arm of the manikin. A Fastrak™ sensor was also attached in a secure position to the superior polystyrene surface of the LC System payload. The resultant location was 305 mm superior and 48 mm posterior to the payload centre of gravity (COG). Displacement data, for the kit payload with respect to the source, was recorded for 10 seconds at 55 Hz every 300 seconds over the duration of the test. Translation from the superior payload sensor location to the loaded pack centre of gravity was performed to provide estimated displacement vectors between the centre of gravity of the loaded LC system and the manikin.

Direct comparison of Fastrak™ positional data with data collected from an opto-electric positional recording system (Optotrak™ by Northern Digital Incorporated) with high precision (RMS error <0.01 mm) provided an RMS error for Fastrak™ data of 0.65 mm.

7.1.10 Reaction Forces and Moments

Ground reaction forces and moments were collected using a 6 degree-of-freedom load cell (AMTI Incorporated) based on a body fixed coordinate system located at the hip and oriented along the long axis of the trunk. The outcomes from this instrumentation were reported as a resultant mean force (N), in which reaction forces in the Fx (forward and back), Fy (side to side), and Fz (up and down) directions were combined vectorially. Similarly, a resultant mean moment (Nm) was defined by combining the Mx (lateral), My (flexion/extension), and Mz (torsional) moments.

Two factors affect the moments and forces transmitted through the load cell: motion and mass of the moving bodies. In the LC simulator, the mass of the torso requires a significant reaction under the imposed displacement from the positioning actuators. This is in addition to the reactions needed to move the payload itself. This is a constant effect for the two ALC systems tested and so the results can be compared directly.

7.1.11 Skin Contact Pressures

An F-Scan^{TM} pressure sensor system (Tekscan Incorporated) was used to acquire contact pressure data on the manikin skin over the anterior shoulder, posterior shoulder, scapula and low back region. Figure 2.1-4 shows the orientation of the F-Scan™ 9810 pressure sensors, which were affixed to the manikin with a non-permanent spray adhesive. The F-Scan™ system uses a matrix of force sensitive resistors, which are arranged in a rectangular pattern and contained between two flexible polyester plastic sheets. At full size there are 96 force sensitive resistors, spaced over a region 206 mm by 76 mm. When the thin polymer foil in an element is compressed, the voltage passed across the element changes. This change is sensed by system software, and is recorded as a load normal to the sensor surface, based on individual calibration for each sensor. Information is transferred to the computer through a signal processing unit and cable to a computer card. This information can be replayed in "movie" format, which can give a dynamic measurement of force, average and peak pressures, active area, or duration of contact. Previous testing at Queen’s (DCIEM Contract #W7711-4-7225/01-XSE) has found the F-Scan™ system standard error of the mean to be 9.6 % for average pressures and 14 % for peak pressures. Also, use of the sensors on a curved surface leads to a 9% standard error of the mean for average pressure results (MacNeil, S.K. 1996)

For LC system testing, pressure data were reported in terms of peak dynamic pressures (kPa) and average pressure over all active cells of the sensors (kPa) in the anatomical areas of interest; anterior shoulder, posterior shoulder (scapula), hip, and lower back

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(U) A modification from Velco® and strapping to a sewn attachment method for the shoulder straps of the Clothe the Soldier (CTS) Rucksack was evaluated for: load control, dynamic peak loading and pressure distribution to the torso. Quantitative assessment of these functional parameters was undertaken to compare the behaviour of a proposed modification to that of the currently fielded design to ensure no degradation in performance. This modification was proposed to address problems that have arisen with the current shoulder strap attachment when loads carried in the rucksack increased from 25 to approximately 45 kg.

The CTS load carriage system includes the Tactical Vest (TV), the Rucksack, and a Small Pack System which have been designed to be compatible. In addition to wearing the TV and one of the packs, soldiers are increasingly attempting to wear the Fragmentation Protection Vest (FPV), with Bullet Resistant Plates (BRP) beneath the TV and Rucksack.

The purpose of testing was to quantify any impact of the modified shoulder attachment design on the following parameters: a soldier’s load control ability, the pressure distribution under the rucksack, the range of motion of the trunk or the mechanical energy cost of walking. Both CTS designs were tested dynamically on the Load Carriage Simulator and on the Compliance tester.

Results showed no significant effects on the load carriage parameters examined and consequently no significant change is anticipated in the CTS rucksack performance in terms of load control, pressure distribution, torso range of motion or energy cost should this modified shoulder strap attachment method be adopted.

(U) La modification proposée au mode de fixation des courroies d’épaules du sac à dos Habillez le soldat (HLS), visant à passer d’un mode de fixation par Velco® et sangle à un mode de fixation cousu, a été évaluée en fonction du contrôle de la charge, des pointes de charge dynamiques et de la répartition de la pression sur le torse. Une évaluation quantitative de ces paramètres fonctionnels a été effectuée pour comparer le comportement du mode de fixation proposé à celui en service, afin de déterminer s’il y avait diminution du rendement. La modification a été proposée pour régler les problèmes de fixation des courroies d’épaules qui sont survenus lorsque les charges transportées dans le sac à dos sont passées de 25 à environ 45 kg.

Le système de transport de charge HLS comprend la veste tactique (VT), le sac à dos et l’ensemble musette et sacs. Tous ces composants ont été conçus de manière à être compatibles. De plus en plus souvent, les soldats tentent de porter la veste pare−éclats (VPE) avec plaques pare−balles (PPB) en plus de la VT et du sac à dos.

Les essais visaient à mesurer l’impact du mode de fixation modifié des courroies d’épaules sur les paramètres suivants : capacité de contrôle de la charge par le soldat, répartition de la pression sous le sac à dos, amplitude du mouvement au niveau du torse et dépense d’énergie mécanique pendant la marche. Les deux modes de fixation ont été soumis à des essais dynamiques sur le simulateur de transport tactique et l’appareil d’essai de conformité de transport tactique.

Les résultats n’ont démontré aucun effet important sur les paramètres de transport de charge examinés. Par conséquent, si la modification au mode de fixation des courroies d’épaules est adoptée, on ne prévoit aucun changement important au niveau du rendement du sac à dos HLS en ce qui a trait au contrôle de la charge, à la répartition de la pression, à l’amplitude du mouvement au niveau du torse ou à la dépense d’énergie.

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(U) Clothe the Soldier; CTS; Load carriage system; rucksack; modified shoulder attachment; load carriage simulator; compliance tester; pressure measurement system

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